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LAKE ECOLOGICAL EVALUATION AND LAND USE PLANNING IN LAKESIDE AREA FROM THE PERSPECTIVE OF TWO-WAY INTERACTION

Evaluación ecológica de un lago y planificación del uso del suelo en la ribera desde la perspectiva de la interacción bidireccional

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Key words: NPS pollution, pollution holding capacity, lake ecological health assessment index, land use, lakeside landscape, urban planning.

ABSTRACT

The healthy development of the lakeside area needs a detailed assessment of lake ecology and land use, and to adopt a targeted dynamic maintenance strategy. This paper is based on the micro perspective. On the one hand, through the subdivision of land use types in lakeside area, the paper discusses the impact of non-point source (NPS) pollution from different types of land on lake ecology. On the other hand, the paper studies the impact of water environmental capacity and water ecological health assessment on lakeside area construction. From a two-way perspective, we can unify the two as a whole, and jointly promote the healthy development of the lakeside area. Studies have shown that the construction of lakeside area needs to control scale and land use types to meet the needs of water ecological protection. The 2-levels, 5-categories, and 17-subcategories of the lake ecological health assessment index can provide effective support for dynamic monitoring and optimization and adjustment of planning strategies. Lakeside area developing is a dynamic and gradual process. The paper provides a feasible method to realize lake ecological protection and urban development.

Palabras clave: contaminación no puntual, capacidad de carga contaminante, índice de determinación de salud ecológica de lagos, paisaje ribereño, planeación urbana.

RESUMEN

El desarrollo saludable de la ribera de los lagos requiere una evaluación detallada de la ecología del lago y el uso de la tierra, y adoptar una estrategia de mantenimiento dinámica específica. Este artículo se basa en la micro perspectiva. Por un lado, a través de la subdivisión de los tipos de uso de la tierra en la ribera del lago, el documento analiza el impacto de la contaminación por fuentes no puntuales de diferentes tipos de tierra en la ecología del lago. Por otro lado, el documento estudia el impacto de la capacidad ambiental del agua y la evaluación de la salud ecológica del agua en la construcción de áreas lacustres. Desde una perspectiva bidireccional, podemos unificar los dos en su conjunto, y promover conjuntamente el desarrollo saludable de la ribera del lago. Los estudios han demostrado que la construcción de la ribera del lago necesita controlar la escala y los tipos de uso de la tierra para satisfacer las necesidades de protección ecológica del agua. Los dos niveles, cinco categorías y 17 subcategorías del índice de evaluación de la salud ecológica del lago pueden proporcionar un apoyo eficaz para el seguimiento dinámico y la optimización y ajuste de las estrategias de planificación. El desarrollo de la ribera del lago es un proceso dinámico y gradual. El documento proporciona un método factible para realizar la protección ecológica del lago y el desarrollo urbano.

INTRODUCTION

The development of lakeside area needs to consider as a whole with lake ecological conservation. The two are a unified whole. Land use change brought by lakeside construction (Su et al. 2014) will challenge the lake ecology (Jacobson 2011, van Roon and Knight 2004). Existing studies are more from a macro perspective, through remote sensing image recognition and other methods (Wilson 2015), to explore the impact of land use change on lake ecology. Due to the limitation of analysis accuracy, the methods may ignore micro differences caused by different land types, which will limit the planning response of lakeside area. Good ecological environment and urban spatial quality have become the guarantee and goal of lakeside area developing. We should emphasize the balances between development and environmental protection during lakeside construction, which include the balances between dynamic development and static protection, between ecological and economic benefits, between the natural environment and urban landscape, between ecological conservation and land use, and between environmental capacity and construction volume (Yang et al. 2019). Under the general principle of balanced developing, the only way to realize the sustainable development of lakeside area is to seek moderate development within the framework of ecological conservation.

Considering lakeside area construction from the micro perspective, it has its particularity and practical needs. We should consider lakeside area and the water body as a unified whole. The two are interdependent and complementary. First, the prosperous development of lakeside area is based on water quality maintenance. Ecological health determines the path of urban development. Second, under the premise of effective control of pollution sources, lakeside areas construction can promote water protection and enhance water vitality. Through the establishment of an index and dynamic evaluation of water ecological health, it can provide a reference standard for urban construction in lakeside area, as well as a reference for planning strategies and policy optimization.

The catchment area is most closely associated with the lake, which does not only include natural water flow. Meanwhile, the scale of urban construction, as well as land use in the area, exert a decisive influence on the water quality of the lake (Palla and Gnecco 2015). From the perspective of the water body, the lake is like a large sponge facility (Walker and and Lucke 2019), as it can effectively regulate water volume, degrade pollutants, form the urban landscape, and accommodate diversified animals and plants. Thus, we should pay high attention to the lake, including the spatial distribution and carrying capacity of pollutants, its pollution holding capacity, and the hydrodynamic properties of the water flow (Yang et al. 2019). Corresponding design strategies and measures should be adopted to improve the self-purification capacity of the water body during urban planning. Under the premise of maintaining a healthy water environment, we should enhance the resilience of the water body during urban development (Aerts et al. 2014). Pollutant distribution and the impact of urban construction on the lake are determined by the urbanization degree surrounding the water. They are also affected by geological features, lake properties, and biological environment, including area, volume, depth, water retention period, sediments, and species (Meyer 2009).

Pollution load arising from lakeside construction can be classified into two main categories, namely, point source (PS) pollution of municipal sewage and NPS pollution in the catchment area. With the gradual improvement of municipal infrastructure, we can collect and treat PS pollution fully and compliantly via the sewage pipeline system. Therefore, the prevention and control of NPS pollution have become the key concern for lakeside development (Yan et al. 2019). NPS pollutants flow to lakes mainly through rainfall runoff and adversely affect the water environment. NPS pollution load is closely related to the types and scale of urban land use. Such load varies widely by land use types (Meyer 2009). NPS pollution load can be calculated by comprehensively considering the factors, such as topography and landforms, land usage, runoff and drainage, and catchment area, as well as indicators like runoff coefficient and pollutant concentration of rainfall runoff. Given their correlation, NPS pollution load, water environmental capacity, and land use can constitute a mutual feedback calculation mechanism and optimize land use planning under the quantitative situation of the water environment. Land use management in the lakeside area involves multiple aspects and requires transdisciplinary research. In view of this, diversified methods should be adopted to reach the established objectives (Liu et al. 2007).

Lake ecological health assessment is a vital means to achieve the sustainable development of the lakeside area. Many scholars have proposed the definitions and criteria of ecological health (Costanza et al. 1992, Karr 1993, Rapport et al. 1998), explored varied applications of lake evaluation methods, and put forward different evaluation systems (Rapport 1992, Karr 1993, Edsall et al. 2004). Evaluation indicators can be classified into three major categories, that is, ecological indicators, human health and economic and social indicators, and physical and chemical indicators (Jørgensen 1999). Lakeside development is a lake-centered process that seeks coordinated and sustainable development among urban construction, economic development, human vitality, and ecological protection by establishing environmental protection and utilization frameworks. It embraces a wide scope, including non-material characteristics, such as society, economy, culture, and communities, and material characteristics like space, ecology, and landscape (Kumar et al. 2013). Hence, the evaluation system of lake health should be developed from a more comprehensive perspective to enrich the connotations of sustainable development. The existing health evaluation indices pay more attention to the water body. They lack evaluation indicators for the lakeside area, and neglect the treatment of the relationship between water and lakeside area.

The paper tries to respond to the needs of lakeside construction from a micro perspective with a more refined evaluation method. Lakeside area developing is a dynamic and gradual process. The implementation of refined evaluation needs to be based on diversified data collection, detection and evaluation. Through the establishment of an evaluation index, we can overall consider of the lake water and lakeside area construction, and then make corresponding dynamic adjustments to promote the healthy development of the lakeside area. This paper provides a feasible method for the realization of lake ecological protection and lakeside benign development.

MATERIALS AND METHODS

Case selection and data source

The paper focuses on two cases: Xianghu Lake in Hangzhou, Zhejiang, and Heilong Lake in Chengdu, Sichuan. The former is in the Yangtze River Delta region, East China, while the latter locates in the Sichuan Basin, West China, as shown in **figure 1**. Both cases are urban development projects centering on a lake. The logic of case selection is to explore the universality of the method. The two cases are different in topography, climate, economic development level, etc. Xianghu Lake is located in the economically developed eastern region of China. It has been connected with the city and belongs to subtropical monsoon climate with four distinct seasons. Heilong Lake is located in the economically underdeveloped western region. It is an urban enclave with mild climate, less sunshine and plentiful rainfall.

The main data types in this study include: 1) Onsite measured data, such as water quality sampling data, lake landscape, soil types, animal and plant sampling, and topographic and landform characteristics, 2) historical statistics, such as rainfall statistics, historical hydrological data, and aerial data; and 3) other data, such as land use types and construction scale (**Table I**).

Analysis of NPS pollution load in catchment area and pollution holding capacity of the lake

Calculation of NPS pollution load

For the estimation of the runoff NPS pollution load, the rainfall runoff volume should be calculated first. The Runoff Curve Numbers (small-area catchment runoff model) proposed by the United States Department of Agriculture-Soil Conservation Service (USDA-SCS 1985) are employed, as shown in the equations below:

$$q = \begin{cases} \frac{(P-0.2S)^2}{P+0.8S}(P \geq I_a) \\ 0\ (P < I_a) \end{cases} \tag{1}$$

$$S = \left[\frac{25400}{C_N}\right] - 254 \tag{2}$$

Wherein P represents a rainfall (unit: mm), while C_N, the rainfall-runoff coefficient, reflects the runoff yield of the basin underlayer unit. In general, it is a function of land use types, soil types, or antecedent moisture conditions. The value of C_N is decided by rainfall, land use eigenvalue, and runoff depth.

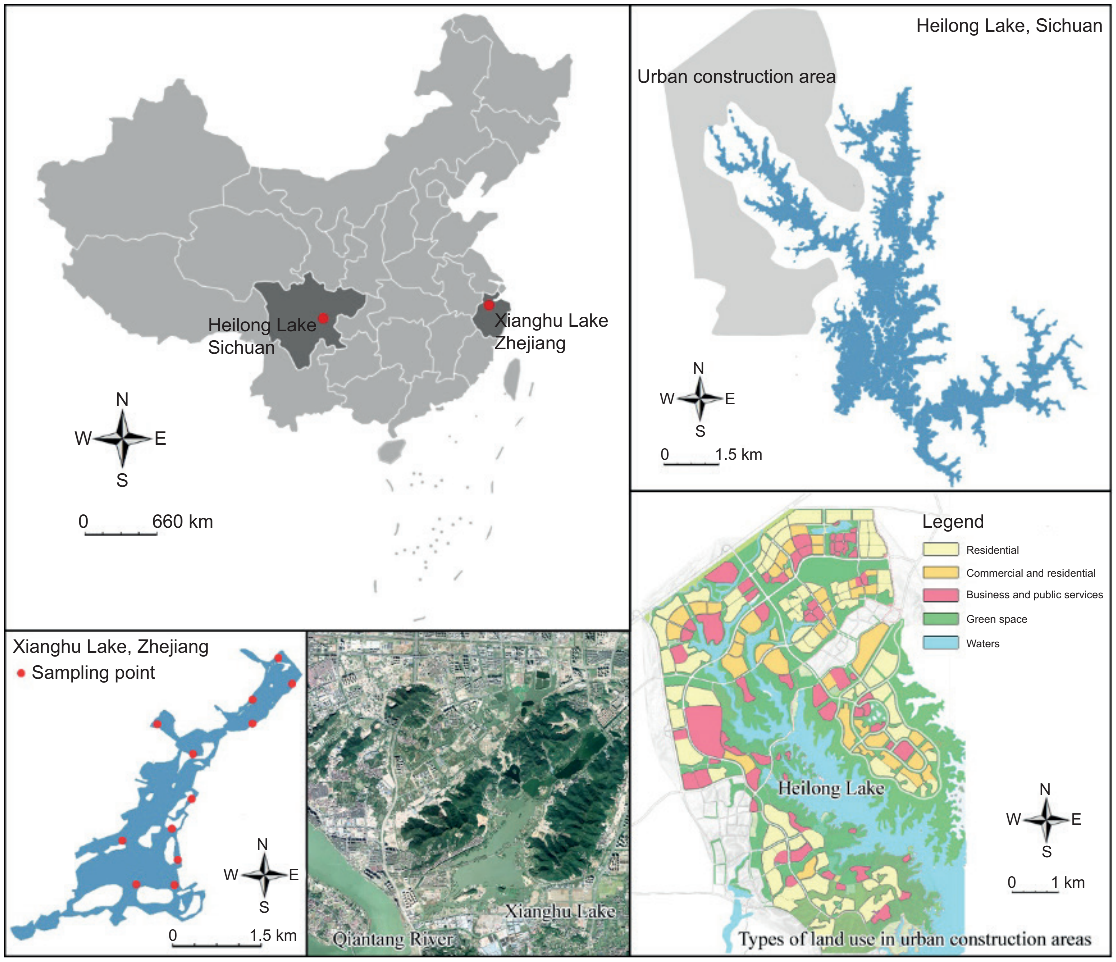

Fig. 1. Location map of the two lakes. The on-site water quality sampling time of Xianghu Lake was December 16, 2017. It was a sunny day and the air temperature was 4-15ºC.

TABLE I. DETAILS OF STATISTICAL ANALYSIS DATA COLLECTION.

Data types	Data details	Collection methods	Collection purpose
On-site measured data	Water quality sampling data	Sampling method, Field Collection	to evaluate the quality of lake ecology and landscape environment
	Soil types	Sampling method, Field Collection	
	Animal and plant sampling	Site survey and historical data sorting	
	Lake landscape	Site survey	
	topographic and landform characteristics	Site survey and historical data sorting	
Historical statistics	Rainfall statistics	Historical statistics	to calculate rainfall and surface runoff, etc.
	historical hydrological data	Historical statistics	
	Aerial data	Historical statistics	
Other data	land use types	Urban planning data	to calculate the total amount of pollutants that may be generated by lakeside construction
	Construction scale	Urban planning data	

Ranging from 25 to 98, C_N indicates land surface condition, land use or soil permeability, and antecedent moisture condition (**Table II**).

In **table I**, A, B, C, and D refer to the soil types that differ by permeability: A represents thick sandy soil, thick loess, and granulated silty soil, while B, thick sandy soil and sandy loam; C, sandy clay; and D, clay loam, silty clay fill, sandy clay, silty clay, and clay. The soil type in the Heilong Lake reservoir basin is yellow clay that is acid, viscous, and easy to harden. Accordingly, it falls into Type C.

The antecedent moisture conditions (AMCs) are characterized by three degrees (C_N (I): Dry; C_N (II): Normal; and C_N (III): Wet) by antecedent precipitation. For the urban area, if a five-day precipitation total (P5d) is lower than 36 mm, the AMC is C_N (I). If P5d is between 36 mm and 53 mm, the AMC is C_N (II). And if P5d is higher than 53 mm, the AMC is C_N (III). See **table III** for the values of C_N (II). The modifier formulas of C_N (I) and C_N (III) are below:

$$C_N(\mathrm{I}) = \frac{C_N(\mathrm{II})}{2.234 - 0.01334 C_N(\mathrm{II})} \quad (3)$$

$$C_N(\mathrm{III}) = \frac{C_N(\mathrm{II})}{0.4036 - 0.0059 C_N(\mathrm{II})} \quad (4)$$

Calculation of pollution holding capacity of the lake

The pollution holding capacity of the lake is associated with many factors, including water volume, the target value of water quality, comprehensive degradation coefficient, and input and output water yield. Without regard to the mixing zone, when the mass concentration of the water function zone is required to be Cs, the formula of the environmental capacity will be as follows (Yang et et al. 2019):

$$W_{capacity} = 31.54 \times (QC_s + KC_sV \div 86400) \quad (5)$$

where $W_{capacity}$ is the environmental capacity (*t/a*); Cs is the target value of water quality (mg/L); Q is the input and output water yield at steady state; k is the comprehensive degradation coefficient of COD and ammonia; V is the water volume in lake and reservoir (m^3).

Coupling analysis of calculation results

Lakes and their surrounding urban construction can be mutually checked by calculating NPS pollution load and water environmental capacity. If the pollution load is smaller than water environmental capacity, the general development is proved to be healthy and sustainable. Otherwise, the planning strategy should be adjusted to ensure the balanced and

TABLE II. REGIONAL C_N VALUES IN A TYPICAL CITY.

Different land use types		C_N			
		A	B	C	D
Residential area		77	85	90	92
		61	75	83	87
		57	72	81	86
Commercial area		89	92	94	95
Industrial area		81	88	91	93
Lawns, parks, golf courses, cemeteries, etc.	Fertile lawns (coverage > 75%)	39	61	74	80
	Average lawns (coverage: 50%-75%)	49	69	79	84
	Barren lawns (coverage < 50%)	68	79	86	89
Streets and roads	Paved roads with curbs and storm drain	98	98	98	98
	Pebble and gravel roads	76	85	89	91

sustainable development of the lakeside area. Such adjustments include reducing the development size, adding ecological purification facilities, controlling the pollution source, and raising the water environmental capacity.

Water ecological health evaluation system

Water ecological health assessment and monitoring is an activity of multiple values, including ecological, social, and cultural values. Basic ecological preservation is the foundation and starting point of development. Sustainable development of the lakeside area integrates the pursuing of multiple values, such as economy, society, ecology, space, and culture. The lake will be shaped into the core of the visual landscape, human activities, and ecological protection. Thus, this paper referred to an existing research framework, centered on water quality, hydrology, and ecosystem indicators, and added lake landscape criteria, while building the indicator system (**Table III**), in order to evaluate lake health more comprehensively. The health assessment has become a bridge between lake ecology and lakeside development. It can also integrate the two into a whole, and realize the two-way interaction between the two aspects.

RESULTS

Mutual feedback calculation of development scale and water volume

Lake health is closely correlated with lakeside development and construction. Factors like land use types, construction scale, and density will all influence the accumulation of water pollutants. A mutual feedback calculation mechanism between urban development and construction and water environmental capacity can be established to guide the surrounding construction. In the case of Heilong Lake, a check mechanism of land use, construction scale, and water environmental capacity was established, based on the quantitative analysis of land use planning and water environmental capacity, to facilitate the formulation of the planning scheme.

The rainfall value in the research area was based on the rainfall statistics of Chengdu City for 2015. The annual precipitation of Chengdu City in 2015 was 873 mm, slightly lower than the multi-year average precipitation of 918 mm, so it was a representative value regarding the calculation of the NPS pollution load. There were 130 rainy days in 2015, wherein the precipitation of 97 days was lower than 5 mm. In general, when the precipitation reaches 5 mm, the land surface will be completely wet, followed by infiltration and detention. Runoffs will form in streets when the precipitation reaches 5-10 mm. The year 2015 witnessed 33 effective rainfalls with effective precipitation of 551.2 mm, accounting for 63% of the annual precipitation. See **table IV** below for detailed effective precipitation.

The rainfalls by C_N (I: Dry), C_N (II: Normal), and C_N (III: Wet) were 26, 2, and 5, respectively in accordance with the daily effective precipitation of Chengdu City in 2015. The C_N values under different AMCs were calculated with the modifier formula (**Table IV**). The net rainfalls of different land use types under different AMCs were calculated with the SCS model and summed up to obtain the annual runoff volume. Moreover, the runoff coefficient was calculated accordingly (**Table V**).

The total annual runoffs of each land use type in the planned area could be calculated by multiplying the land use area with the annual net rainfall of each land use type. Then, the water quality data of some Chinese cities, such as Xi'an, Beijing, and Chengdu, as well as the pollutant concentration in the direct surface runoff of each land use type were considered. COD, TN, and TP were chosen as indicators for calculation. The NPS pollution load of rainfall runoff in the planned area was estimated by multiplying the annual effective precipitation with the pollutant concentration. Pollutant concentration was appropriately simplified during the estimation of this paper. The average concentrations (Li 2000) were: COD, 190 mg/L; TN, 15 mg/L; and TP, 0.8 mg/L.

In general, the pollutant output coefficient plays an essential role in the estimation of pollution load, as it decides the NPS pollution output in the catchment area. Different underlying surfaces and land use types can cause the coefficient to fluctuate. By measurement standards, the pollutant output coefficient can be classified into two types, namely, output load coefficient per unit area (kg/hm^2/a) and Event Mean Concentration (EMC) (mg/L) of rainstorms. The output load coefficient per unit area refers to the annual average total pollutant output per unit area in a specific area. It is more applicable to rural areas. EMC reflects the total pollutant output per unit runoff volume. It is more suitable to calculate the load of urban land use types (Lin 2004). The total annual runoff volume can be calculated based on the area of each land use type in the lakeside area. Then, the NPS pollution loads of COD, TN, and TP can be obtained. Besides, NPS pollution load and water environmental capacity can be mutually checked.

TABLE III. WATER ECOLOGICAL HEALTH EVALUATION INDEX.

Criteria	Indicators	Description of indicator	Quantitative standards	Data source
Water quality characteristics, B1	Nemerow multi-factor index (C11)	Pollutant properties and pollution degree	COD, NH_3-N, TN, and TP	Measured data
	Trophic level index (TLI) (C12)	Eutrophication level and transparency of the lake	TLI	Measured data
	Dissolved oxygen (C13)	An important indicator that reflects the self-purification capacity of the lake	DO	Measured data
Hydrological characteristics, B2	Compliance with the lowest ecological water level (C21)	Ecological safety indicator and measurement factor used to maintain ecological stability of the lake	Compliance rate of the lowest ecological water level	Statistics
	Water renewal cycle (C22)	Water flow and hydrodynamic indicator	Water renewal cycle	Statistics
Physical morphological structure, B3	Stability of lake basin (C31)	Maintenance of morphological structure	Stability of lake basin	Measured data Statistics
	Lakeshore stability (C32)	Ecological safety indicator	Lakeshore stability	Measured data Statistics
	Vegetation integrity (C33)	Plays a role in lake landscape creation, resistance against water and soil loss, and biological conservation	Vegetation coverage	Measured data Remote sensing data
	Shoreline form and bank protection method (C34)	Indicator of the natural ecology of the lake	Hardening rate of the bank slope	Measured data Statistics
Ecosystem indicators, B4	Vegetation coverage of green belts (C41)	Ecological environment quality measurement indicator	Coverage of buffer zone, slope, and island	Measured data Remote sensing data
	Biodiversity (C42)	Biodiversity measurement indicator	Phytoplankton diversity	Measured data Statistics
	Indigenous plant conservation rate (C43)	Indicator of the anti-interference capacity of the ecosystem	Proportion of indigenous plants	Measured data Statistics
	Proportion of natural water body (C44)	Degree of interference of human activities	Proportion of natural water body	Measured data Remote sensing data
	Habitat quality indicator (C45)	Main parameter of lake habitat diversity	Lake habitat diversity indicator	Measured data Statistics
Lakeside landscape, B5	Aesthetic measurement (C51)	Landscape diversity, richness, and aesthetic measurement indicator	Aesthetic measurement	Measured data
	Landscape accessibility (C52)	Indicator of freedom and convenience of the public to access lake landscape	Landscape accessibility	Measured data Remote sensing data
	Width of lakeside green belts (C53)	Lakeside green belt quality measurement indicator	Lakeside greening rate	Measured data Remote sensing data

TABLE IV. SCS MODEL-BASED STATISTICAL TABLE OF EFFECTIVE PRECIPITATION OF CHENGDU CITY FOR 2015 (UNIT: mm).

Date	Precipitation	Date	Precipitation	Date	Precipitation
March 5	5.4	May 29	7.4	September 9	62.5
April 5	17.7	June 19	14.2	September 16	7.8
April 8	6.1	June 23	39.6	September 17	15.5
April 9	11.6	August 24	7.1	September 22	16.3
April 30	19.1	August 26	38.3	September 26	5.7
May 1	16.2	August 27	7.9	October 18	8.1
May 8	5.3	September 2	33.1	October 22	15.3
May 20	7.4	September 3	37.3	October 23	10.5
May 21	14.8	September 4	25.1	November 11	6.3
May 22	8.0	September 5	9.8	November 23	6.4
May 24	9.0	September 8	50.2	December 18	6.2

TABLE V. SUMMARY OF ANNUAL NET RAINFALLS OF DIFFERENT LAND USE TYPES UNDER DIFFERENT AMCs.

Land use type	C_N			Annual net rainfall/mm	Runoff coefficient
	I	II	III		
Residential area	87	90	96	192.36	0.349
Commercial and residential area	91	92	97	234.78	0.426
Commercial area	93	94	98	273.26	0.496
Health maintenance area	74	83	93	126.02	0.229
Education industry area	91	92	97	234.78	0.426
Commercial area in scenic spots	87	90	96	192.36	0.349
Entertainment area in scenic spots	87	90	96	192.36	0.349

Scoring of lake ecological health risk evaluation

The indicator system developed above was utilized to evaluate the ecological health of Xianghu Lake. In addition, lakeside landscape indicators were added to the system. Finally, a lake ecological health evaluation indicator system consisting of two levels, five categories, and 17 sub-categories was created.

Indicators of water quality characteristics, B1

The indicators of water quality characteristics are significant parameters of lake health, including the Nemerow multi-factor index (C11), the trophic level index (TLI) (∑) (C12), and dissolved oxygen (DO) (C13).

The formula of the Nemerow multi-factor index (Nemerow, 1971) is as follows:

$$I_i = \sqrt{\frac{\left(C_{imax}\right)^2 + \left(C_{iave}\right)^2}{2}} \tag{6}$$

Wherein, I_i represents the multi-factor index of the i-th monitoring point, while C_{imax}, the maximum single-factor index of the i-th monitoring point; and C_{iave} the average single-factor index of the i-th monitoring point. The formula of the single-factor index is below:

$$C_{ij} = \frac{C_p}{C_s} \tag{7}$$

Wherein, C_{ij} refers to the single-factor index of the j-th pollutant at the i-th monitoring point, while C_p, the actual monitored value of the j-th pollutant at the i-th monitoring point; and C_s, the standard value of the j-th pollutant at the i-th monitoring point. By calculating and scoring the Nemerow multi-factor index (**Table VI**), it can evaluate the water quality by the indicator.

For the trophic level index TLI(∑) (C12), there are five trophic parameters to be measured, namely, Chla (mg/m^3), TP (mg/L), TN (mg/L), lake transparency SD (m), and COD_{Mn} (mg/L). The formula of the TLI(∑) is as follows:

$$\mathrm{TLI}\left(\sum\right) = \sum_{j=1}^{5} w_j \times \mathrm{TLI}(j) \tag{8}$$

TABLE VI. SCORECARD OF NEMEROW MULTI-FACTOR INDEX.

Nemerow multi-factor index	< 1	1-2	2-3	3-5	> 5
Score	4	3	2	1	0

Wherein, w_j represents the weight of the j-th trophic level index, while TLI(j), the corresponding trophic state index. Chla is regarded as the benchmark parameter. See the formula of the weight of each trophic parameter w_j, below:

$$w_j = \frac{r_{ij}^2}{\sum_{j=1}^{5} r_{ij}^2} \tag{9}$$

Wherein, r_{ij} represents the correlativity of the j-th parameter to the benchmark parameter. The correlativity of Chla, TP, TN, SD, and COD_{Mn} to Chla were 1, 0.84, 0.82, -0.83, and 0.83, respectively.

See the formula of the nutritional state index of each nutritional parameter below:

$$\mathrm{TLI}(chl) = 10\left(2.5 + 1.086\ln hl\right) \tag{10}$$

$$\mathrm{TLI}(TP) = 10\left(9.436 + 1.624\ln TP\right) \tag{11}$$

$$\mathrm{TLI}(TN) = 10\left(5.453 + 1.694\ln TN\right) \tag{12}$$

$$\mathrm{TLI}(SD) = 10\left(5.118 - 1.94\ln SD\right) \tag{13}$$

$$\mathrm{TLI}(COD_{Mn}) = 10\left(0.109 + 2.661\ln COD_{Mn}\right) \tag{14}$$

The final calculation results and score evaluation criteria are shown in **Table VII**.

TABLE VII. TLI SCORECARD.

Nutritional index	< 30	30-50	50-60	60-70	> 70
Score	4	3	2	1	0

DO (C13) was mainly rated based on the measured and sampled data, the scoring standards are shown in **Table VIII**.

TABLE VIII. DO SCORECARD.

DO (mg/L)	≥ 7.5	≥ 6	≥ 5	≥ 3	≥ 2
Score	4	3	2	1	0

Lastly, the evaluation results of Xianghu Lake water quality characteristics were obtained based on the scorecards of the Nemerow multi-factor index, the TLI, and DO, as shown in **Table IX**.

TABLE IX. EVALUATION RESULTS OF XIANGHU LAKE WATER QUALITY CHARACTERISTICS.

Indicator	Nemerow multi-factor index (C11)	TLI (C12)	DO (C13)
Score	3	2	1.55

Indicators of hydrological characteristics, B2

The evaluation indicators of hydrological characteristics mainly include compliance with the lowest ecological water level (C21) and the water renewal cycle (C22). The first indicator (C21) can be determined based on historical statistics, the scoring standards are shown in **Table X**.

$$\text{Water renewal cycle(C22)} = \frac{\text{lake storage}}{\text{runoff volume to lake}} \tag{15}$$

The scoring standards of the water renewal cycle are shown in **table XI**. The water from the Qiantangjiang River has been transferred to the Phase III Project of Xianghu Lake since December 2016.

TABLE X. SCORECARD OF COMPLIANCE WITH THE LOWEST ECOLOGICAL WATER LEVEL.

Compliance of lowest ecological water level	Score
All the daily average water levels of 365 days of a year are higher than the lowest ecological level.	4
The daily average water level is lower than the lowest ecological level, but the three-day average water level is not.	3
The daily average water level is lower than the lowest ecological level, but the seven-day average water level is not.	2
The seven-day average water level is lower than the lowest ecological level.	1
The 14-day average water level is lower than the lowest ecological level.	0

TABLE XI. SCORECARD OF WATER RENEWAL CYCLE.

Water renewal cycle (d)	< 25	25-50	50-100	100-200	> 200
Score	4	3	2	1	0

Through Shiyanshan River, Xianghu Lake is connected with Nanmenjiang River, Xiaoshan District. The quality water from the Qiantangjiang River has been transferred to the downtown area of Xiaoshan, through Xianghu Lake, resulting in effective water circulation. The water renewal cycle of Xianghu Lake is around 30 days after the water transfer, leading to a good hydrodynamic field and water quality.

The Xianghu Lake Resort Area is built along Xianghu Lake. Watershed concentration and the waterpower of Qiantangjiang River are employed to maintain a low ecological water level of Xianghu Lake in order to protect the function of Xianghu Lake as lungs for the city. See the evaluation results of the hydrological characteristics of Xianghu Lake below (**Table XII**).

TABLE XII. EVALUATION RESULTS OF HYDROLOGICAL CHARACTERISTICS OF XIANGHU LAKE.

Indicator	Compliance of lowest ecological water level (C21)	Water renewal cycle (C22)
Score	4	3

Physical structure, B3

These indicators include the stability of lake basin (C31), lakeshore stability (C32), vegetation integrity (C33), and shoreline form and bank protection method (C34). The scoring standards of the stability of the lake basin are shown in **Table XIII**.

See **Table XIV** for the scoring criteria of lakeshore stability (C32).

TABLE XIII. SCORECARD OF STABILITY OF LAKE BASIN.

Stability of lake basin	Very stable	Stable	Average	Unstable	Extremely unstable
Score	4	3	2	1	0

TABLE XIV. SCORECARD OF LAKESHORE STABILITY.

Lakeshore stability	Score
Stable lakeshore without obvious erosion	4
Stable lakeshore with erosion in a few areas (< 20%)	3
Somewhat unstable lakeshore with moderate erosion (20%-50%)	2
Unstable lakeshore with extreme erosion (50%-80%) and risks in case of a flood	1
Extremely unstable lakeshore with erosion in most areas (80%-100%)	0

Vegetation integrity (C33) mainly refers to the coverage of arbor, shrub, and lawn, and the scorecard of vegetation integrity is shown in **table XV**. The respective formula is shown as follows:

$$\text{Vegetation coverage} = \frac{\text{vegetation coverage of bank slopes}}{\text{total area of bank slopes}} \tag{16}$$

See the following scoring criteria (**Table XVI**) of shoreline form and bank protection method (C34):

In consideration of the field survey and historical materials, the lake basin and shoreline of Xianghu Lake are stable with little erosion. The shoreline is heavily covered by vegetation and protected with stone blocks, cement mortar or soil. See **table XVII** for the evaluation results of the physical structure of Xianghu Lake.

TABLE XV. SCORECARD OF VEGETATION INTEGRITY.

Vegetation coverage (%)	> 75	50-75	25-50	5-25	< 5
Notes	Extremely heavy coverage	Heavy coverage	Moderate coverage	Sparse vegetation	Extremely sparse vegetation
Score	4	3	2	1	0

TABLE XVI. SCORECARD OF SHORELINE FORM AND BANK PROTECTION METHOD.

Shoreline form	Score
Natural soil bank slope with vegetation	9-10
Near-nature inclined ecological slope protection	7-9
Waterborne platform slope protection or soil bank slope without vegetation	5-7
Step-like artificial slope protection or stone blocks with cement mortar	3-5
Vertical reinforced concrete	0-3

TABLE XVII. EVALUATION RESULTS OF THE PHYSICAL STRUCTURE OF XIANGHU LAKE.

Indicator	Stability of lake basin (C31)	Lakeshore stability (C32)	Vegetation integrity (C33)	Shoreline form (C34)
Score	3	3	3	4

Ecosystem indicators, B4

The sub-categories of ecosystem indicators mainly include vegetation coverage of green belts (C41), biodiversity (C42), indigenous plant conservation rate (C43), proportion of natural water body (C44), and habitat quality indicator (C45).

$$\text{Vegetation coverage of green belts (C41)} = \frac{\text{area of green belts for lake covered with vegetation}}{\text{total area of green belts for lake}} \tag{17}$$

Upon evaluation, the vegetation coverage of the shoreline, slope, and island of Xianghu Lake was approximately 85%. Hence, the score was 4.

Biodiversity (C42) mainly refers to the species diversity in the lake, which is often expressed with the Shannon's diversity index (SHDI) (Shannon and Weaver 1963). It can be classified into five levels. The formula of the SHDI is below:

$$\mathrm{H} = -\sum_{i=1}^{s} P_i \times \log_2 P_i \tag{18}$$

$$P_i = \frac{n_i}{N} \tag{19}$$

Wherein, s represents the total number of species in all samples, while n_i, the total number of each species in the samples; N, the total number of living things in the samples. The scoring standards of the biodiversity index are shown in **table XVIII**.

The numbers of phytoplankton and zooplankton were obtained through on-site investigation and sampling. The biodiversity index of Xianghu Lake was 3.

Indigenous plant conservation rate (C43) indicates whether indigenous plants are advantageous among plants and reflects the anti-interference strength of the ecosystem. A higher value corresponds to better strength. Upon investigation, most plants in the slope, island, and shoreline of Xianghu Lake were indigenous. The indigenous plant conservation rate was 90%. The corresponding score was 4.

TABLE XVIII. SCORECARD OF DIVERSITY OF PHYTOPLANKTON AND ZOOPLANKTON.

SHDI (H)	> 3	2-3	1-2	0-1
Score	4	3	1	0

This indicator demonstrates the degree of interference of human activities in the lakeside area. Based on the on-site investigation and aerial measurement, the proportion of the natural water body of Xianghu Lake was approximately 45%. The corresponding score was 2.

Habitat quality indicator (C45) is the main parameter of Lake Habitat diversity, focusing on water depth, flow rate, and matrix. The MIKE model (DHI Group) was used to calculate the flow field of Xianghu Lake. The lake has different flow rates and depths. Submerged plants were found in some water areas. Thus, the corresponding score was 3. Finally, the evaluation results of ecosystem indicators of Xianghu Lake are shown in **table XIX**.

Lakeside landscape, B5

The most direct change brought by lakeside development and construction lies in the visual landscape. The original natural landscape is transformed into an urban landscape formed both naturally and artificially. Since the lakeside landscape is the most advantageous and attractive landscape resource in the area, its fairness, openness, and accessibility should be fully considered when designing its spatial arrangement, so that the lakeside landscape can contribute to regional development, public health, and social harmony. The public spatial system, building height and volume, land use, business pattern, and visual landscape in the lakeside area should be coordinated during planning and design to realize the established sustainable

TABLE XIX. EVALUATION RESULTS OF ECOSYSTEM INDICATORS OF XIANGHU LAKE.

Indicator	Vegetation coverage of green belts (C41)	Biodiversity-SHDI (C42)	Indigenous plant conservation rate (C43)	Proportion of natural water body (C44)	Habitat quality indicator (C45)
Assignment	4	3	4	2	3

development goals. These indicators include aesthetic measurement (C51), landscape accessibility (C52), and the width of lakeside green belts (C53).

With respect to the evaluation of aesthetic measurement (C51), the strategy of an on-site questionnaire or on-site scoring by experts can be adopted. A statistical summary can then be performed over the results to determine the level and score of the lakeside landscape, the scoring standards are as follows (**Table XX**).

TABLE XX. SCORECARD OF AESTHETIC MEASUREMENT OF LAKE.

Aesthetic measurement	Excellent	Good	Medium	Pass	Poor
Score	4	3	2	1	0

Landscape accessibility (C52) is evaluated from four main aspects, namely, the space, visual effect, continuity, and comfort of the landscape, the final score can be calculated (**Table XXI**) through quantitative evaluation of the factors.

The width of lakeside green belts (C53) was determined and scored based on the on-site measured and aerial data (**Table XXII**).

TABLE XXII. SCORECARD OF WIDTH OF LAKESIDE GREEN BELTS.

Average width of green belts (m)	> 30	20-30	15-20	10-15	< 10
Score	4	3	2	1	0

Xianghu Lake, as a national resort area, features a beautiful landscape, complete infrastructure, developed transportation, and good landscape accessibility. See **table XXIII** for its landscape evaluation results. For future lakeside development, landscape aesthetics should be deemed as a key point of urban construction and included in the evaluation system to highlight its importance.

TABLE XXI. SCORECARD OF LANDSCAPE ACCESSIBILITY.

Landscape accessibility	High accessibility	Somewhat high accessibility	Average accessibility	Somewhat low accessibility	Low accessibility
Description	Special lanes for the disabled and children; walkways, bikeways, and motorways; no buildings within 50 meters of the shoreline, tier-1 buildings less than four stories, tier-2 buildings less than 10 stories, and buildings less than 10 stories within 100 meters of the shoreline; good sanitary conditions, adequate lighting, and a patrol.	Suitable passageways; walkways and bikeways; no buildings within 50 meters of the shoreline, tier-1 buildings less than four stories, tier-2 buildings less than 10 stories, and buildings less than 20 stories within 100 meters of the shoreline; good sanitary conditions, moderate lighting, good security, and a low migrant population.	Not suitable for the disabled and children; only walkways; no buildings within 50 meters of the shoreline, tier-1 buildings less than 10 stories, tier-2 buildings less than 20 stories, and buildings less than 30 stories within 100 meters of the shoreline; some rubbish, inadequate lighting, average security, and some migrants.	Not suitable for the disabled and children; only motorways; no buildings within 50 meters of the shoreline, tier-1 buildings less than 10 stories; some rubbish, extremely inadequate lighting, with security risk, and many migrants.	Impossible for the disabled and children to pass through; no accessible roads; buildings more than 10 stories within 50 meters of the shoreline; rubbish everywhere, no lighting, poor security, and few passers-by.
Score	4	3	2	1	0

TABLE XXIII. LANDSCAPE EVALUATION RESULTS OF XIANGHU LAKE.

Indicator	Aesthetic measurement (C51)	Landscape accessibility (C52)	Width of lakeside green belts (C53)
Score	4	3	4

General scoring

A judgment matrix with a scale ranging from 1 to 9 was developed based on the scores of the above indicators. The weights of each category and each sub-category were confirmed. When coupled with the scores of indicators, the comprehensive index of lake health risk was obtained. In accordance with the existing evaluation levels and criteria, the final results were classified into five levels, namely, excellent, good, moderate, poor, and very poor. The importance of water quality and the ecosystem indicators were stressed, while weights were distributed. The final evaluation level of Xianghu Lake was good, with a score of 2.95 (**Fig. 2**).

The establishment of the evaluation system is conducive to evaluating the health condition of the lake from multiple factors in a comprehensive, regular, and long-term manner. Furthermore, the evaluation results serve as a reference for the optimization of sustainable development in the lakeside area. Ecological protection and urban development are balanced, while lake health is maintained.

DISCUSSION

Lakeside development is subject to many factors. Regarding urban construction, lake health is a key factor that cannot be neglected. Maintaining lake health is an effective way to guarantee long-term regional development. Lakes are a core factor in lakeside development, closely related to urban functions, activities, economy, culture, and landscape. This paper explores the coupling and interaction between lake health and lakeside development and aims to discover a way to achieve harmony between these two elements based on the above analysis methods. The final goal is to realize sustainable lakeside development (Rauch and Morgenroth 2013). Many other aspects can be further discussed during the application of the methods.

The subjective influence of factor weights and scoring in the aquatic ecological health evaluation index

In evaluation index composing, the influence of human subjective reasons is bound to exist, from evaluation factors determination to factor weights distribution to the finalization of the final scores of various factors, etc. Especially under the unifying principle of highlighting one body and two sides, we add factors of landscape environmental quality to the evaluation index, which intensifies the degree of subjective influence. Through the evaluation and scoring of Xianghu Lake, it was carried out from the five aspects of water quality, hydrology, physical form and structure, ecosystem, and lakeside landscape. The final score was 2.95, and the water ecology was healthy. Different subjects can use the same evaluation index to score, but the final scores may have certain differences. This is also the external manifestation of subjective influence, so we need to discuss and explain.

Selection of factors for water health evaluation indicator system

Factor selection is a key aspect when establishing the water health evaluation indicator system,

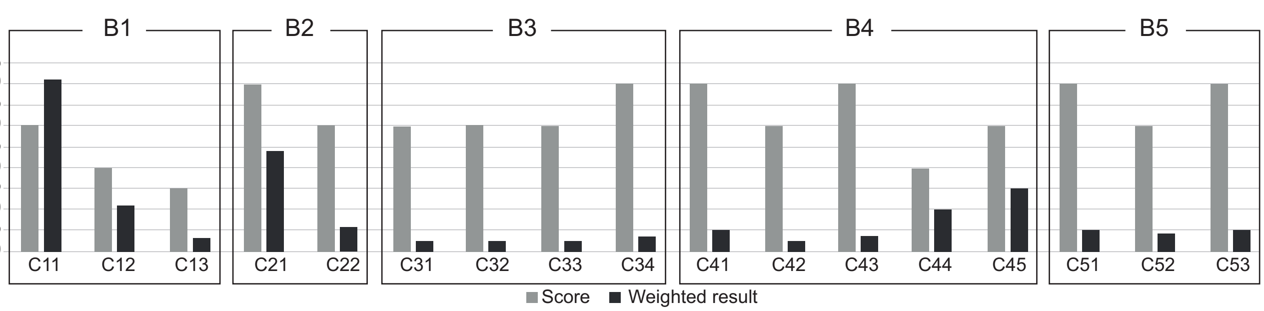

Fig. 2. Scores and weights of Xianghu Lake's indicators based on the water ecological health evaluation indicator system (Note: The weights were uniformly amplified by five times for the convenience of comparative analysis, as shown by the dark bars in the figure.)

as it reflects value orientation. Scholars have not reached a consensus on how to select factors due to their flexibility. That said, ecological and hydrological factors assume a dominant position in the system. This paper highlights the comprehensive and sustainable development of the lakeside area. Besides the existing factors of the ecosystem, water quality, and hydrology, an extra factor measuring lakeside landscape was added to the evaluation system. Sustainable lakeside development contains rich connotations, encompassing the fields of ecology, society, culture, and landscape. Thus, factors should be selected conscientiously for the indicator system to strengthen the comprehensive evaluation value of the indicator system.

Definition of lake pollution source

The quantitative calculation of this paper is based on the subjective definition of water pollution sources. It was assumed that PS pollution could be treated 100% effectively. Therefore, only the total NPS pollution in the catchment area was measured and compared with the pollution holding capacity of the lakes. However, the effective treatment rate of PS pollution, in fact, cannot reach 100%, especially in the area with rapid development yet incomplete municipal infrastructure. PS pollution emission can greatly affect lakes, posing challenges to the identification of treatment methods. It is suggested that we should measure the water environmental capacity of pollutants in a flexible manner, while attaching high importance to NPS pollution. The allowable collection rate of municipal sewage should be measured and estimated. PS pollution is closely associated with land use type. The quantitative calculation can be conducted in combination of the land use type and size in the catchment area to effectively evaluate the allowable collection rate of municipal sewage.

Simplification error of EMC method

The pollutant concentration in the direct surface runoff of each land use type was determined, while the total NPS pollution was calculated. The NPS pollution load of rainfall runoff in the planned area was estimated by multiplying the annual effective precipitation with the pollutant concentration. By calculating the EMC of each land use type, the method proposed in this study can simplify the research operation to a certain degree, causing deviations in the final results. The EMC of each land use type was clarified to calculate pollutant load more accurately. Regions and time periods are also dynamic factors that should be fully considered in the calculation of EMC. During lakeside construction, the development size should be under proper control to reduce the total NPS pollution. It would be better for the environment if lakeside lands are mainly used for residential and commercial use. Measures like an increase in the green area and provision of ecological purification facilities are conducive to a higher resilience of lake ecology.

Improvement measures for lake environmental capacity and response to lakeside construction

In general, the pollution holding capacity of a lake is directly proportional to its water volume and flow rate. The water ecology will worsen when the total pollution surpasses the sum of the critical value of pollution holding capacity and total outflow of the lake. Therefore, an increase in flow rate can effectively enhance water environmental capacity when water volume remains stable. Other improvement measures include the enhancement of self-purification capacity and control of pollution sources. During lakeside construction, ecological pollution control technology can be utilized as a feasible way to treat pollution, including low-impact development (LID), sponge cities, and water-sensitive urban design (WSUD). Multi-layer and multi-type NPS pollution elimination systems can be created through constructed wetlands, floating islands for ecological purification, aquatic vegetation, green roof, and rainwater gardens to control the adverse influence of NPS pollution in lakes. The application of the DHI MIKE model serves as a reference for the optimization of hydrodynamic indicators and water quality (Yang et al. 2019). Improvement in water environmental capacity is significant for lakeside construction. On the premise of protecting the environment, we can accelerate the development and construction in urban areas and their surrounding areas.

CONCLUSIONS

Lakeside development, with the treatment of the water body at the core, coordinates the development of urban construction, human activities, ecological landscape, animals, and plants. To adopt a scientific and reasonable method is a necessary and effective way for regional sustainable development. Lake health is vital to the future development of the lakeside area. In order to realize the goal of sustainable development, it is necessary to consider both the lake and urban construction. The effective connection between lake health and urban development is inseparable from the balances between pollution load and water environmental capacity, and between dynamic urban construction and lake health evaluation. Sustainable lakeside development is a broad concept, covering water safety, health, and circulation. Additionally, its connotations keep enriching and gradually go beyond the perspectives of this paper, i.e., space and ecology. In other words, sustainable lakeside development shows diversified and comprehensive value orientation, which conforms to the final goal of sustainable development, to sustain or improve the quality of life for all.

In the paper, we have explored the method for the refined evaluation of lakeside area developing from the micro perspective, which can improve the existing method system and provide new evaluation tools. However, in the process of method application, we still need to combine different site characteristics and goal orientation to formulate the corresponding evaluation index. With the enrichment of connotative goals, the selection of index factors and weight distribution have become the core content. In order to ensure the effective implementation of the method, it requires high-quality urban management to support, such as the effective control and reduction of pollution sources, and the application of sponge city measures, which can also effectively promote the healthy development of the lakeside area.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

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